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An Intelligent Healthcare Management System: A New Approach in Work-order Prioritization for Medical Equipment Maintenance Requests

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Abstract The effective maintenance management of medical technology influences the quality of care delivered and the profitability of healthcare facilities. Medical equipment maintenance in Jordan lacks an objective prioritization system; consequently, the system is not sensitive to the impact of equipment downtime on patient morbidity and mortality. The current work presents a novel software system (EQUIMEDCOMP) that is designed to achieve valuable improvements in the maintenance management of medical technology. This work-order prioritization model sorts medical maintenance requests by calculating a priority index for each request. Model performance was assessed by utilizing maintenance requests from several Jordanian hospitals. The system proved highly efficient in minimizing equipment downtime based on healthcare delivery capacity, and, consequently, patient outcome. Additionally, a preventive maintenance optimization module and an equipment quality control system are incorporated. The system is, therefore, expected to improve the reliability of medical equipment and significantly improve safety and cost-efficiency.

Keywords Biomedical technology management · Work-order prioritization · Preventive maintenance · Quality control

Introduction

Safe, effective, and economic use of medical devices within a hospital requires tracking each individual device. The number of medical devices requiring tracking and management in a hospital may range from 1,000 devices for smaller community hospitals to over 10,000 for large, academic, medical centers [1]. Wang et al. have indicated that the most common cause of medical equipment downtime is poor maintenance, planning, and management. Consequently, they have extensively discussed and reviewed medical equipment inclusion criteria, as well as the application of statistical techniques, in medical equipment management plans [2, 3]. Medical equipment management is of particular importance in developing countries, where resources and alternatives are scarce, as such, the creation of a carefully-designed equipment control and management system can be of vital importance. This can be achieved by employing computerized maintenance management systems (CMMSs) as a fundamental information resource, providing the technology management staff with a wealth of support-related information as well as assisting management in decision making [1].

Additionally, as medical equipment becomes increasingly more sophisticated and plays a more crucial role in modern healthcare, maintenance and management issues demand ever-increasing attention. Development of CMMSs is essential for managers and engineers, not only to provide quick management solutions, but also to predict future outcomes based on historical equipment performance data. The most commonly employed methods of work-order prioritization for repair requests in Jordan are variants of the first-come, first-served (FCFS) method. While the FCFS approach might be acceptable for many applications, it is not always appropriate when applied to the healthcare sector, as is the case when a vital, life-support machine undergoes failure and, consequently, is out of service until the service work-order reaches the head of the queue. One approach to address these shortcomings requires that

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hospitals maintain a full-time equipment oversight committee to prioritize all maintenance requests. Unfortunately this is a time- and cost-intensive approach. Another approach suggests focusing on the risk posed by equipment failure on larger groups of patients, rather than focusing on the equipment with the highest maintenance demand [4]. Some authors have suggested categorizing systems according to their level of complexity as a guide for system management, optimization, and cost reduction, [5] as well as proposing a rule base for real-time equipment replacement prioritization [6]. While various commercial computerized maintenance management systems are available, [7] there is little objective published work available. The model presented herein relies on an intelligent work-order prioritization system. It enables the medical service provider to construct a real-time prioritized equipment service list for submitted maintenance requests based on various predefined factors such as equipment function, location of use, time since request was issued, availability and distance to nearest substitute, and the overall rate of equipment utilization.

Industrial maintenance management information technology systems have been in use for many years. The research has addressed equipment classification systems, preventive maintenance (PM) scheduling models, and work-order systems for prioritizing repair requests for industrial facilities and manufacturing companies, [8–12] but very few of these systems have addressed the specific needs of the healthcare management field. Commonly accepted maintenance policies include age-replacement PM, [13] as well as the periodic PM and sequential PM policies [14]. In the periodic PM policy, devices subject to degradation are maintained in fixed predefined time intervals, independent of machine failure rate, while in a sequential PM policy the PM time intervals become shorter and shorter as time passes (i.e. more frequent PM is required as the device ages). Other studies, such as those carried out by Badia et al. [15] Berenguer et al. [16] and Yang et al. [17] attempted to optimize PM periods by relying on the continuous assessment of the equipment condition and attempting to predict the level of performance degradation. We propose a model adapted from the work of Adzakpa et al. [18] that utilizes an optimization algorithm for PM periods and combines it with a fixed periodic PM approach, to yield higher accuracy and stability.

Incorporating a quality control module into the CMMS can provide objective, quantitative, and reliable assessment of equipment performance. Such approaches include those based on the quality function deployment (QFD) approach [19]. This approach allows service to be tailored towards the actual demand, and is characterized by a “semi-quantitative” and objective approach to quality assessment in healthcare structures. Generally the accuracy of assessing a medical device’s reliability increases as the size of the performance statistics database increases [20, 21]. While such models represent an advanced tool for quality control measurements, it is highly sophisticated and computationally complex, as such a simpler model requiring a smaller data set would be beneficial.

There are numerous models that deal with PM optimization, work-order prioritization, and quality control in the industrial sector, but little work has focused on the application of these models to the healthcare sector. As a result, many of the existing models focus on minimizing the cost of service delivered rather than the human cost of equipment downtime and failure. Consequently, this work aims to develop a system that addresses these issues with particular stress on human cost, well-being and safety.

Material and methods

This study presents an intelligent medical equipment management system named EQUIMEDCOMP. The system was programmed using Microsoft Visual Basic (version 6). The overall flow chart of EQUIMEDCOMP is illustrated in Fig. 1a and b, which show the system’s various modules, tools, equations, and databases, as well as the relationship between them.

EQUIMEDCOMP can be utilized to carry out multiple medical equipment management-related tasks. The system was designed in a modular format to allow independent development of the individual modules (subsystems). These subsystems include medical equipment inventory, work-order system, PM scheduling system, and equipment quality control system.

Medical equipment inventory subsystem

The first and the most critical step in implementing an equipment management system (computerized or non-computerized) is to build an extensive inventory of all the equipment to be tracked by the program. Without an effective inventory system, it is impossible to track equipment-management functions accurately.

The proposed system is supplied with an extensive medical equipment inventory that continuously tracks all services being performed on each medical device. Each device has an equipment control number (ID); the control number is assigned automatically by the system during device registration, and is used for identification within the system. In addition to the ID number, the system records basic technical information, such as the serial number, device name, type, manufacturer, model, location of use, manufacture date, acquisition date and cost, installation date, equipment function, and the number of preventive maintenance tasks specified by the manufacturer per year.

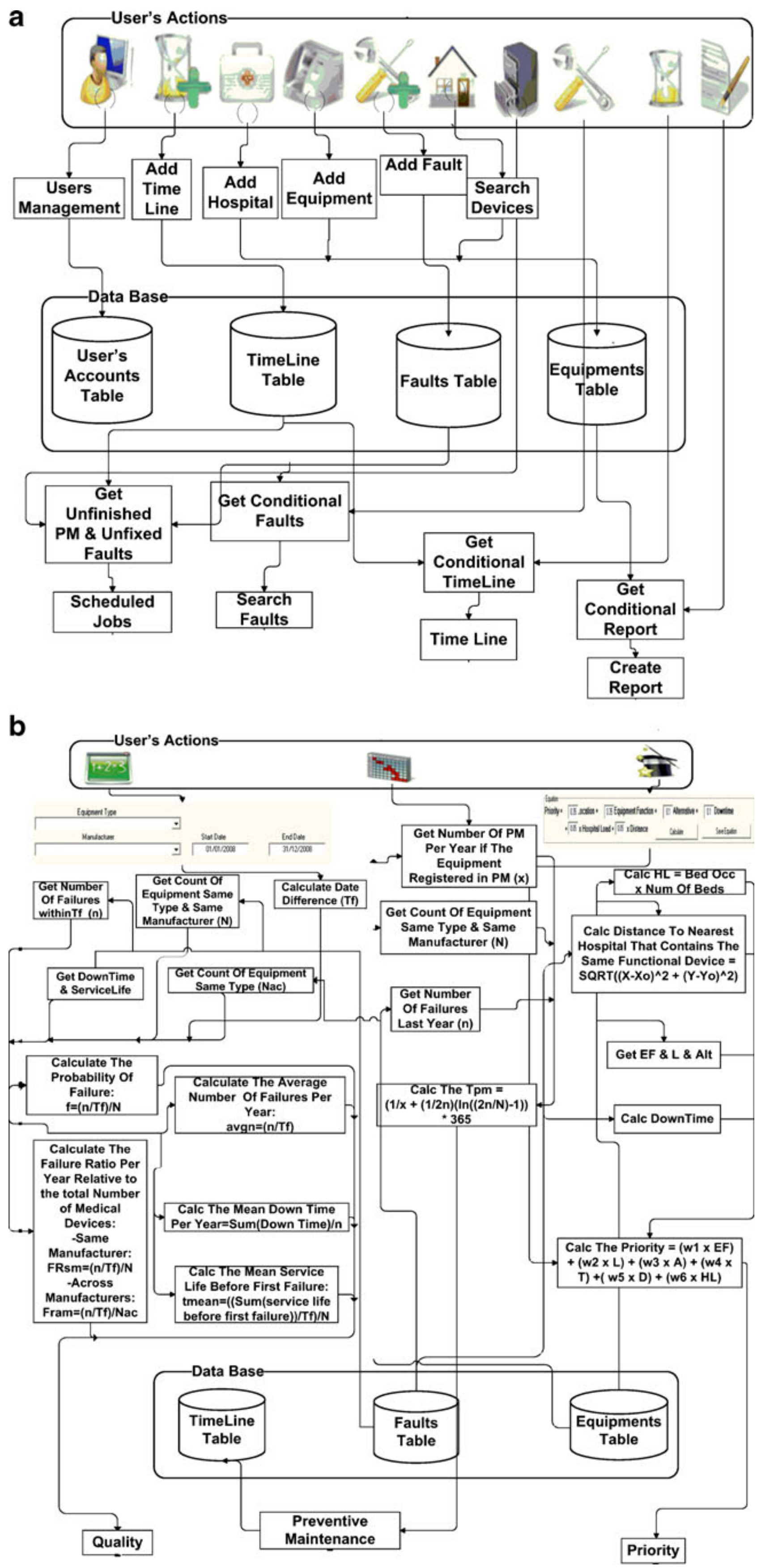


Fig. 1 **a**: EQUIMEDCOMP system flow chart demonstrating the functionality of the equipment inventory subsystem. The various commands (shown as icons) and their interconnections with databases or tables (shown as cylinders) are demonstrated. **b**: EQUIMEDCOMP system flow chart demonstrating the work-order prioritization, PM scheduling, and quality control subsystems

All data, except for the ID number, is acquired during an equipment registration procedure through a web portal. The well organized and user-friendly environment is designed to facilitate and speed-up the process of data entry.

The system is also equipped with a complete hospital database which includes basic information about hospitals in contract with the service-providing agency. This information may include the hospital name, address, city, zip code, GPS coordinates, phone number, fax, website, e-mail, number of beds, and bed occupancy percentage, among other facts.

A third database includes records of the company's service employees and their basic information. This feature provides a means of communication between employers and employees, allows for easier job allocation between biomedical equipment technicians, and holds records of employees' work activity.

The system is equipped with searching options that can be used to find any device within the system's inventory. The search process could be initiated according to one or more of the following: Equipment ID, hospital name, equipment type, and equipment name.

Work-order subsystem for prioritizing maintenance requests

An important feature that is incorporated into our system is a work-ordering subsystem that assigns a priority number for each unscheduled maintenance request. This subsystem documents incoming requests for maintenance services and keeps track of the work-order until completion. The priority number for any request represents a calculated numeric value indicating the relative importance of that request. It enables the system to qualify a certain request to be more important than another based on its medical necessity and patient safety.

Upon entering the system, a maintenance request is subjected to a special testing algorithm consisting of six factors, each of which assigns a certain numeric value to that request. These factors test the importance of the request based on the following criteria: (1) equipment function, (2) location of use, (3) the load on the hospital containing the failed device, (4) the presence of an alternative to this device in the hospital, (5) time since maintenance request in days, and (6) distance to the nearest hospital containing the same type of device for which maintenance is requested. The priority number of each request is then calculated as a weighted sum of six different numeric values developed by each factor, and the device with the highest priority number is serviced first. Numerical weights assigned to the various factors were determined by conducting recursive iterations of the prioritization algorithm towards optimal work-order sequences, as deemed by the expert opinions of local physicians and clinical engineers; these values may be found in Tables 1 and 2.

Table 1 The values assigned to equipment by function and location

Equipment function (EF)	
EF	Numeric value
Therapeutic - Life-support	10
Therapeutic - Surgical or Intensive Care	9
Therapeutic - Physical Therapy or Treatment	8
Diagnostic - Surgical or Intensive Care Monitoring	7
Diagnostic - Other physiological monitoring	6
Analytical - Laboratory	5
Analytical - Computer and related	3
Miscellaneous - Patient-related	2
Miscellaneous - Non-patient related	1
Location of equipment use (L)	
L	Numeric value
Anesthetizing Locations	5
Critical Care Areas, Operational Rooms	4
Wet Locations/Labs/Exam Areas	3
General Patient Care Areas	2
Non-Patient Care Areas	1

Table 2 The values assigned to equipment based on hospital load (size), time since service was requested, and distance to nearest alternative of the device in question

Hospital Load (number of beds)			
HL	Numeric Value	HL	Numeric Value
>550	12	251–300	6
501–550	11	201–250	5
451–500	10	151–200	4
401–450	9	101–150	3
351–400	8	51–100	2
301–350	7	0–50	1
Time (in days)			
T	Numeric Value	T	Numeric Value
>10	22	5	10
10	20	4	8
9	18	3	6
8	16	2	4
7	14	1	2
6	12		
Distance to nearest alternative (km)			
D	Numeric Value	D	Numeric Value
>90	26	20.1–30	12
80.1–90	24	10.1–20	10
70.1–80	22	5.1–10	8
60.1–70	20	2.1–5	6
50.1–60	18	1.1–2	4
40.1–50	16	0–1	2
30.1–40	14		

Any equipment registered in the system is assigned an equipment function (EF) number indicating the functional category of the device, as seen in Table 1. In this regard, therapeutic life-support equipment is considered more important to a patient's life than equipment in other functional categories, and thus receives a higher numeric value. In other words, the most crucial equipment receives the highest numeric value and, as a result, if it fails it receives the highest priority number.

Another requirement of equipment registration in the system is to specify the location in which the equipment is used; consequently a numeric value (L) is given for each device indicating the area in which it is primarily used. The system sorts equipment into five categories, as indicated in Table 1. Devices used in operating rooms (OR) and critical care areas receive a higher numeric value (greater priority) as their failure represents an imminent threat to a patient's life.

Since bed occupancy reflects the percentage of the total number of beds that are occupied by patients at any given time, it may be used to assess utilization of the facility. The product of hospital capacity (given by the number of beds within the hospital) and bed occupancy may be used as an indicator of the hospital load (HL). As HL increases, the number of patients expected to need a certain device increases, and, as such, the system gives this device a higher priority number. Numeric values assigned to different ranges of HL are indicated in Table 2.

The geographical location of the hospital and the distance to the nearest hospital with an appropriate substitute for the failed device is accounted for within the system. If a device in a certain hospital fails, the system locates the nearest registered hospital within the system database containing an alternate device. This is done with the assistance of a virtual global map, for example Google Earth, and employing the spatial coordinates of the two hospitals according to Eq. 1:

$$D = \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}{1000} \quad (1)$$

Where D is the distance (km) to the nearest hospital containing a similar functioning device, (x_1,y_1) and (x_2,y_2) are the spatial coordinates of the hospital containing the failed device and the nearest alternate, respectively. The equation was divided by 1,000 to express D in kilometers. The system then assigns a higher priority to the device whose alternate is the farthest away, as shown in Table 2.

The presence of an alternative to a device is an important issue to consider. Medical equipment without any substitute within the same hospital should have preference when maintenance is required. The system assigns equipment with no substitute or alternate a higher priority, by giving variable A in Eq. 2 a numeric value of 10 for equipment without any readily available substitute, and setting the value of A to 0 if an alternate is available. The time since the maintenance request was issued (T) is also considered in the system (see Table 2), since equipment requiring maintenance is considered out of service, thus increasing equipment downtime.

Based on these six factors, namely, EF, L, HL, A, T, and D, each device requiring maintenance is given a priority number; the higher the priority number the higher the necessity for maintenance. The priority number, P, is calculated according to Eq. 2:

$$P = (X_1)EF + (X_2)L + (X_3)A + (X_4)T + (X_5)D + (X_6)HL \quad (2)$$

where X_1, X_2, X_3, X_4, X_5, and X_6 are the weights assigned to EF, L, A, T, D, and HL, respectively.

The weight assigned to each factor when computing the priority number was determined based on recursive converging iterations to minimize the prioritization error between expert prioritization (physicians and clinical engineers) and that of the computerized system (EQUIMEDCOMP). The optimum case, which generated the best outputs (least match error), was to assign an approximate weight of 0.35, 0.35, 0.1, 0.1, 0.05, and 0.05 to X_1, X_2, X_3, X_4, X_5, and X_6., respectively. Although these assigned weights produced efficient and realistic outputs in our tests, the administrator has the ability to adjust these values according to his/her professional judgment and the particular institutional requirements, see Fig. 2. As expected, equipment function (EF) and location of use (L) received the highest weight, followed by the presence of an alternative to the failed device within the same hospital (A) and the time since the maintenance request was issued (T), and finally the distance to the nearest alternative (D) and the hospital load (HL).

The data required for the operation of the work-order subsystem is gathered in different stages: information regarding the device location, type, and fault description is entered through the "Add fault" window, seen in Fig. 3. Information regarding equipment function, location of use, and the presence of an alternative within the hospital is assigned when the equipment is registered in the system, as seen in Fig. 4. The system uses the GPS coordinates of a hospital to calculate the minimum distance between it and all other registered hospitals containing an available alternate.

Preventive maintenance scheduling subsystem

Medical equipment failure is an extremely sensitive issue, since every medical device is directly and closely related to the patients' health and well being. Thorough PM can virtually eliminate downtime caused by equipment failure, but the associated cost of such maintenance can be prohibi-

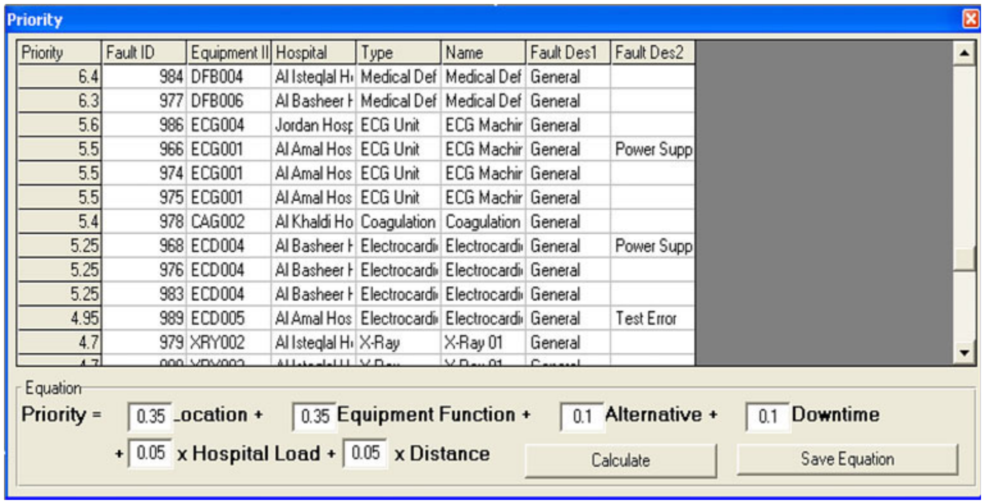


Fig. 2 The EQUIMEDCOMP priority table of devices for which maintenance has been requested and prioritized

tive. Therefore, a compromise must be found that minimizes the cost associated with periodic inspections and extends the durability of medical equipment. It is clear that a properly weighted PM strategy is necessary for medical equipment to operate in the safest and most cost-effective manner.

EQUIMEDCOMP incorporates a preventative maintenance scheduling sub-system that assigns an optimum period between inspections, based on an algorithm adapted from a period optimization approach and the classical fixed period approach.

From the installation time of the device, and assuming exponential behavior, the availability of the device at time t is given by Eq. 3 [18]:

$$A(t) = \frac{\mu}{\mu + \lambda} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t} \tag{3}$$

where μ is the repair rate of the device, which is a measure of how frequently a medical device is repaired, expressed in repairs per hour; and λ is the failure rate of the device, which is a measure of how frequently a medical device undergoes failure, expressed in failures per hour.

The failure rate of a device per year (λ) can be obtained by dividing the total number of failures per year by the cumulative annual operating time of the device as seen in Eq. 4:

$$\lambda = \frac{n}{h} \tag{4}$$

where n is the total number of failures for all devices of the same type and same manufacturer per year, and h is the cumulative annual operating hours for all devices of the same type and manufacturer.

Assuming that almost all medical devices are repairable, the failure rate of a device is set equal to the repair rate (i.e. λ = μ), hence Eq. 3 simplifies to:

$$A(t) = 0.5 + 0.5e^{-2\mu t} \tag{5}$$

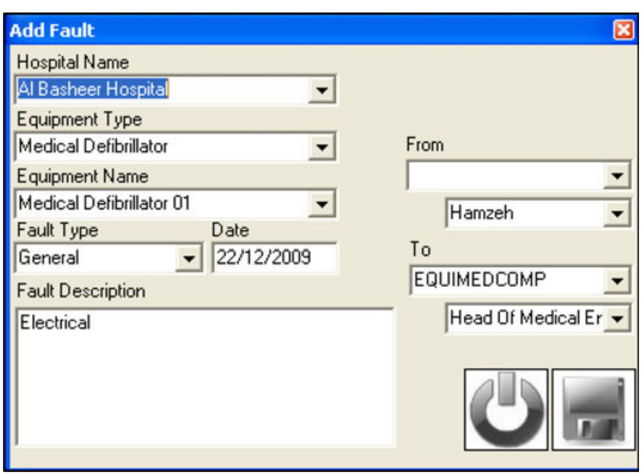


Fig. 3 The "Add fault" window for requesting service for a device registered within the system

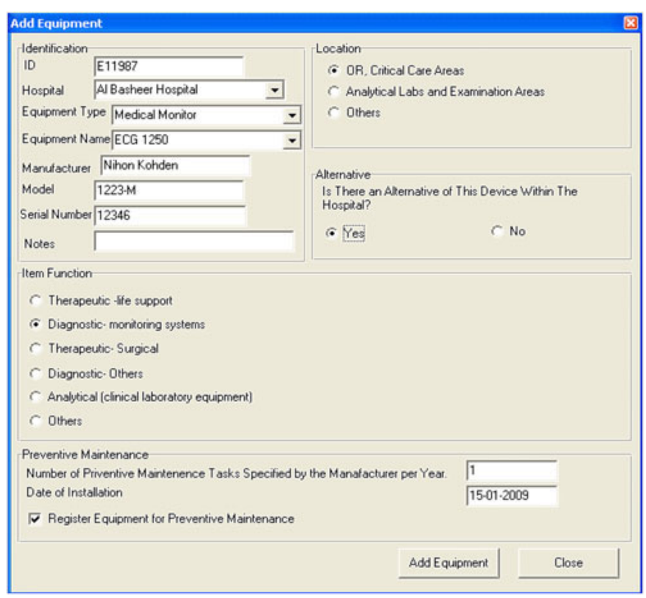


Fig. 4 EQUIMEDCOMP equipment registration window

Clearly, the availability of a device is an exponentially time-decaying function. Consequently, if no maintenance is performed on the device, its availability diminishes toward a threshold value of ω, and whenever A(t) ≤ ω the device is considered unavailable [18]. Accordingly, on account of the constraint that the availability A(t) should always exceed the threshold value ω, the following inequality is derived:

$$A(t) \geq \omega \tag{6}$$

Substituting for A(t) from expression (3) into (6), the latter becomes

$$0.5 + 0.5e^{-2\mu t} \geq \omega \tag{7}$$

From which it may be inferred that

$$t \leq \left(\frac{-1}{2\mu}\right) \cdot \ln(2\omega - 1) \tag{8}$$

The preceding model represents the period-optimizing approach for PM scheduling. EQUIMEDCOMP incorporates this, together with the fixed-periodic approach that is based on scheduled preventive maintenance periods assigned by the manufacturer, to ensure the consideration of the manufacturer's recommendations and at the same time accounting for the state of the device with time, from which Eq. 9 is deduced:

$$\tau_{PM} = \left(\frac{1}{x} + \left(\frac{1}{2\mu}\right) \cdot \ln(2\omega - 1)\right) \cdot 365 \tag{9}$$

where x is the scheduled preventive maintenance rate per year and ω is probability of failure-free work, as represented in Eq. 10

$$\omega = \frac{N - n_{yearly}}{N} \tag{10}$$

where N is the total number of medical devices in the same category and made by the same manufacturer as the device for which PM is required; n_{yearly} is the total number of failures per year occurring in the device requiring PM; and τ_{PM} is the time in days at which the PM should be performed from $t=0$.

If corrective maintenance is carried out on the device at t = T, then the next PM will be scheduled after τ_{PM}, i.e. at $t = T + \tau_{PM}$. The system calculates τ_{PM} only for devices in which PM is specified when the equipment is registered in the system.

Equipment quality control subsystem

The quality of healthcare delivered in modern medical facilities is directly dependant on the state of the medical technology and equipment employed. As such, in order to provide patients with quality medical care, healthcare institutes continually strive to enhance the quality of the medical technology they employ. Developing a technology evaluation system that can perform reliability assessment of medical technology to ensure safe and cost-efficient functionality is of vital importance. The outcomes of this technology assessment can help in planning and deploying future technology requirements, determining whether a particular medical system needs to be replaced, and helping in brand selection of the purchased technology. Usually, the quality evaluation (control) process takes the form of statistical surveys that are performed during the life span of a particular device. These surveys may include various parameters, such as the device's probability of failure, mean downtime, usability, and performance measures. These statistical surveys give insight into the actual performance of medical equipment.

The equipment quality control sub-system employed by EQUIMEDCOMP provides an objective and quantitative reliability assessment for the registered devices. It aids in the identification of equipment that should be replaced, as well as decisions on the subsequent brand selection for new devices being purchased. The sub-system includes an integrated history record (time-line) that keeps track of all maintenance and repair activities performed on a particular device throughout its service life.

The system is capable of carrying out accurate calculations of equipment service life for any selected period of time by generating a quality report, Fig. 5. This report contains a set of parameters that give a quantitative indication of equipment performance. The most frequently used parameters include the probability of failure (Eq. 12), the average number of failures per year (Eq. 13), the failure ratio per year relative to the total number of medical devices (Eqs. 14 and 15), and the mean service life before first failure (Eq. 16). These equations were adapted from the work of Dori et al. [19] and Toporkov, [20] and are given in terms of the time fraction (T_f) as defined in Eq. 11:

$$T_f = \frac{(D_n)}{365} \tag{11}$$

where D_n represents the number of days of the time period over which the quality report is requested, specified by a start and end date that are entered by the user.

The probability of failure (f) is given by

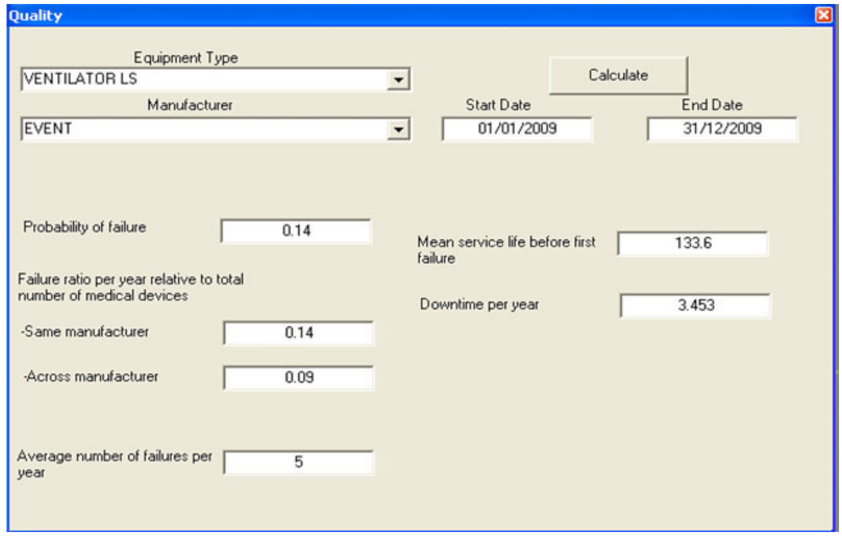
$$f = \frac{n}{N \cdot T_f} \tag{12}$$

where n is the total number of failures within the same category and of the same manufacturer of a medical device, and N is the total number of medical devices of the same category and of the same manufacturer registered within the system.

The average number of failures per year ($\overline{n}$) is calculated from

$$\overline{n} = \frac{n}{T_f} \tag{13}$$

Fig. 5 Quality report window for registered devices



The failure ratio per year relative to the total number of medical devices of the same manufacturer (FR_{sm}) is given as

$$FR_{sm} = \frac{\overline{n}}{N} \tag{14}$$

While the same ratio across manufacturers (FR_{ac}) is given by

$$FR_{ac} = \frac{\overline{n}}{N_{ac}} \tag{15}$$

where N_{ac} denotes the total number of devices across manufacturers.

The mean service life before first failure (t_{mean}) is expressed as:

$$t_{mean} = \frac{\sum_{i=1}^{N} Sl}{N} \tag{16}$$

where Sl is the service life of all medical devices before the occurrence of the first failure.

Other useful parameters employed are the mean corrective maintenance time (Eq. 17), the mean downtime per year (Eq. 18), and the mean time between failures. These equations were adapted from the work of Amari et al., [21]

Table 3 Maintenance requests submitted to a third-party medical service provider within a four-day work period. The time each order was received rounded to the nearest 5 min is indicated

Requests	1st Day	2nd Day	3rd Day	4th Day
1	Blood Cell Counter-Al Bashir Hospital-9:00 AM	Dialysis Unit-Prince Zaid Hospital-8:00 AM	EEG Monitor-Prince Hashem-8:30 AM	Refrigerated Centrifuge-Palestine Hospital- 9:15 AM
2	Anesthetic Ventilator-Prince Hashem Hospital-9:30 AM	Coagulation Analyzer-KAUH- 9:00 AM	Defibrillator-Prince Ali Hospital-9:15 AM	EMG monitor-Private Clinic- 11:30 AM
3	Electrical Bed-Jordan Hospital-10:00 AM	Medical Ventilator-Jordan Hospital-9:20 AM	CT-Prince Ali Hospital-10:00 AM	Medical Refrigerator-JUH-01:45 PM
4	Ultrasound Imager -Princess Haya Hospital-11:00 AM	Therapeutic Ultrasound unit- JUH- 10:10 AM	Defibrillator-Prince Zaid Hospital-11:00 AM	
5	Infusion Pump-Princess Basma Hospital-12:00 PM	MRI-KAUH-11:00 AM	Lithotripsy Machine-Jordan Hospital-12:00 PM	
6	UV imager-KAUH-12:30 AM	X-Ray-Princess Basma Hospital-11:30 AM	Electrosurgical Unit-JUH-1:00 PM	
7	Spectrophotometer-JUH-1:00 PM	ECG Monitor-JUH-12:00 PM	Dialysis Unit -Princess Haya Hospital-2:00 PM	
8	CT-Prince Ali Hospital Hospital-2:00 PM	MRI-Prince Ali Hospital-1:00 PM		
9	Doppler Ultrasound Machine-Ramtha Hospital-2:10 PM	Defibrillator –Ramtha Hospital- 1:30 PM		

Table 4 Maintenance requests for the four-day period sorted using the FCFS method

Request	1st Day	2nd Day	3rd Day	4th Day
1	Blood Cell Counter-Al Bashir Hospital	UV imager-KAUH	Coagulation Analyzer-KAUH	ECG Monitor-JUH
2	Anesthetic Ventilator-Prince Hashem Hospital	Spectrophotometer-JUH	Medical Ventilator-Jordan Hospital	MRI-Prince Ali Hospital
3	Electrical Bed-Jordan Hospital	CT-Prince Ali Hospital	Therapeutic Ultrasound unit-Prince Ali Hospital	Defibrillator –Ramtha Hospital
4	Ultrasound Imager -Princess Haya Hospital	Doppler Ultrasound Machine-Ramtha Hospital	MRI-KAUH	EEG Monitor-Prince Hashem
5	Infusion Pump-Princess Basma Hospital	Dialysis Unit-Prince Zaid Hospital	X-Ray-Princess Basma Hospital	Defibrillator-Prince Ali Hospital

where the mean corrective maintenance time (MCMT) is given by the following expression:

$$MCMT = \frac{\sum_{i=1}^{n} \lambda_i (T_{corr})_i}{\sum_{i=1}^{n} \lambda_i} \tag{17}$$

Such that T_{corr} is the total time duration of corrective maintenance.

The mean downtime per year ($\overline{T}_D$) is given by:

$$\overline{T}_D = \frac{\sum_{i=1}^{n} \left(\frac{T_{D_i}}{T_f}\right)}{\frac{n}{T_f}} = \frac{\sum_{i=1}^{n} T_{D_i}}{n} \tag{18}$$

where $T_{Di} = T_i + (T_{corr})_i$

The mean time between failures (MTBF) in hours is given as the inverse of the failure rate (λ), and the mean time to response (MTTR) is given by:

$$MTTR = \frac{\sum_{i=1}^{n} \lambda_i T_i}{\sum_{i=1}^{n} \lambda_i} \tag{19}$$

The overall function of the equipment quality control sub-system is to generate a quality report containing the above mentioned parameters for any given medical device, manufacturer, or combination of both within a specific time frame, Fig. 5.

Results and discussion

The work-order prioritization system (EQUIMEDCOMP) was simulated and tested against variants of the long-used FCFS approach, such as that employed by the Biomedical Directorate (BMD) in Jordan. Service requests to a third-party medical service provider were used to assess system performance; for demonstration purposes, the results of the first 4 days of testing (28 service requests) are presented in Table 3. For comparison and testing, requests were processed using both the FCFS and EQUIMEDCOMP models. Based on a survey of local medical maintenance service providers it was found that an average service provider could respond to a maximum of five maintenance requests per day, thus any excess maintenance requests are postponed to the following day. The work schedule for the 4-day period using the FCFS method is shown in Table 4.

Table 5 Maintenance requests for the four-day period sorted using EQUIMEDCOMP. The priority number (PN) for each request is indicated

Requests	1st Day	2nd Day	3rd Day	4th Day
1	Anesthetic Ventilator-Prince Hashem Hospital PN=6.7	Therapeutic Ultrasound unit- JUH Hospital PN=6.45	Dialysis Unit-Princess Haya Hospital PN=7.5	Medical Ventilator-Jordan Hospital PN=5.8
2	CT-Prince Ali Hospital PN=6.15	MRI-Prince Ali Hospital PN=6.15	Electrosurgical Unit-JUH PN=6.45	CT-Prince Ali Hospital PN=5.5
3	Infusion Pump-Princess Basma Hospital PN=5.25	MRI-KAUH PN=6.1	Lithotripsy Machine-Jordan Hospital PN=6.1	X-ray- Princess Basma Hospital PN=5.05
4	Ultrasound Imager -Princess Haya Hospital PN=4.65	Dialysis Unit-Prince Zaid Hospital PN=5.9	Defibrillator-Prince Ali Hospital PN=6.05	UV imager- KAUH PN=4.55
5	Doppler Ultrasound Machine-Ramtha Hospital PN=3.75	Defibrillator –Ramtha Hospital PN=5.5	Defibrillator-Prince Zaid Hospital PN=6.0	Blood cell counter - Al-Bashir Hospital PN=4.3

The EQUIMEDCOMP system prioritized the maintenance requests as previously outlined, resulting in a drastically different work schedule when compared to the FCFS method. Factors such as equipment function, location of use, hospital load, time since maintenance request, presence of an alternative, and distance to nearest hospital containing the same device had a notable impact on the prioritization of maintenance requests. Table 5 illustrates the work schedule determined by EQUIMEDCOMP according to the priority number calculated for each of the requests.

It is important to note that postponed requests received a correspondingly higher priority number the following day. For example, the blood cells counter at Al-Bashir Hospital initially received a priority number of 3.7. Accordingly, the device was not listed on the work-order list on the first day. On the second day, that same device achieved a priority number of 3.9, which was still not high enough for it to be included on the work-order list. On the third day, the blood cell counter achieved a priority number of 4.1 which, again, didn't qualify it to be serviced due to the fact that more important requests were introduced that day. However, on the 4th day the device received a score of 4.3, which was sufficient to list and service the device. The same applies to the maintenance request received for the medical ventilator at Jordan Hospital which was received on the 2nd day and was postponed until the 4th day according to its relative importance when compared to other requests.

By comparison, using the FCFS variant, many important high-priority requests were postponed to the following day, including a CT at Prince Ali Hospital, a defibrillator at Prince Zaid Hospital, and a lithotripsy machine at Jordan Hospital. Using the EQUIMEDCOMP work-order prioritization system resulted in the more important requests (greater impact on patient outcome) receiving higher priority, and, consequently, being serviced more rapidly. Additionally, the system's adaptability, with regard to providing operator flexibility and control over the priority equation weight allocation, was greatly appreciated by the companies asked to evaluate the system, since it creates a more dynamic program.

With regard to the PM scheduling sub-unit, a sample of 50 medical devices of the same type and manufacturer were studied. These devices operate normally 9 h per day, 312 days per year, resulting in a total of 2,808 h of operation per year. The average failure rate of the devices was calculated to be 3.205×10^{-3} failures per hour or 8.99 failures per year (Eq. 13). The probability of failure-free work, ω, was then found to be 0.82 (Eq. 10), and the resulting PM time period, τ_{PM}, was calculated to be 175.8 days or 5.78 months (Eq. 9). The PM period scheduling model was sensitive to failure rates of equipment, which, upon implementation, enhanced medical equipment reliability and availability by assigning shorter PM time periods in response to increased failure rate of a particular device.

Finally, the quality control sub-system is an excellent tool for aiding management and engineering staff in decision-making by providing a wealth of information regarding registered medical equipment reliability and performance indices. As an example, the historical performance data for a ventilator was used to generate the 2009 (calendar year) quality report for the device, as shown in Fig. 5. The quality report reveals the device's performance indices for the indicated period, such as, the probability of failure, number of failures, downtime per year, and mean service life before first failure. It will require several years of performance data accumulation before the full potential of this module may be assessed.

Conclusion

The EQUIMEDCOMP work-order prioritization system for medical equipment maintenance management proved its effectiveness in prioritizing maintenance requests. Moreover, it demonstrated sensitivity to patient safety and healthcare quality. The model also aided in more efficient scheduling of PM actions and was responsive to the actual performance of equipment. This, along with quality control indicators, can increase reliability and availability of medical equipment. The system can serve as a comprehensive medical maintenance management system for medical service providers (third-party service providers) and medical service departments of hospitals and governmental healthcare institutions giving quantitative solutions to management problems and ensuring safe and cost-effective operation.

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